Chapter 5
DESIGN REQUIREMENTS

5.1 Seismic Design Categories

The *NEHRP Recommended Seismic Provisions* recognizes that, independent of the quality of their design and construction, not all buildings pose the same seismic risk. Factors that affect a structure's seismic risk include:

- The intensity of ground shaking and other earthquake effects the structure is likely to experience and
- The structure's use including consideration of the number of people who would be affected by the structure's failure and the need to use the structure for its intended purpose after an earthquake.

The *Provisions* uses the Seismic Design Category (SDC) concept to categorize structures according to the seismic risk they could pose. There are six SDCs ranging from A to F with structures posing minimal seismic risk assigned to SDC A and structures posing the highest seismic risk assigned to SDC F. As a structure's potential seismic risk as represented by the Seismic Design Category increases, the *Provisions* requires progressively more rigorous seismic design and construction as a means of attempting to ensure that all buildings provide an acceptable risk to the public. Thus, as the SDC for a structure increases, so do the strength and detailing requirements and the cost of providing seismic resistance. Table 2 summarizes the potential seismic risk associated with buildings in the various Seismic Design Categories and the primary protective measures required for structures in each of the categories.

As noted in Table 2, structures are assigned to a Seismic Design Category based on the severity of ground shaking and other earthquake effects the structure may experience and the nature of the structure's occupancy and use. The nature of the structure's occupancy and use used in determining a Seismic Design Category is broken into four categories of occupancy as summarized in Table 3.

Table 2 Seismic Design Categories, Risk, and Seismic Design Criteria

SDC	Building Type and Expected MMI	Seismic Criteria
A	Buildings located in regions having a very small probability of experiencing damaging earthquake effects	No specific seismic design requirements but structures are required to have complete lateral-force-resisting systems and to meet basic structural integrity criteria.
B	Structures of ordinary occupancy that could experience moderate (MMI VI) intensity shaking	Structures must be designed to resist seismic forces.
C	Structures of ordinary occupancy that could experience strong (MMI VII) and important structures that could experience moderate (MMI VI) shaking	Structures must be designed to resist seismic forces. Critical nonstructural components must be provided with seismic restraint.
D	Structures of ordinary occupancy that could experience very strong shaking (MMI VIII) and important structures that could experience MMI VII shaking	Structures must be designed to resist seismic forces. Only structural systems capable of providing good performance are permitted. Nonstructural components that could cause injury must be provided with seismic restraint. Nonstructural systems required for life safety protection must be demonstrated to be capable of post-earthquake functionality. Special construction quality assurance measures are required.
E	Structures of ordinary occupancy located within a few kilometers of major active faults capable of producing MMI IX or more intense shaking	Structures must be designed to resist seismic forces. Only structural systems that are capable of providing superior performance permitted. Many types of irregularities are prohibited. Nonstructural components that could cause injury must be provided with seismic restraint. Nonstructural systems required for life safety protection must be demonstrated to be capable of post-earthquake functionality. Special construction quality assurance measures are required.
F	Critically important structures located within a few kilometers of major active faults capable of producing MMI IX or more intense shaking	Structures must be designed to resist seismic forces. Only structural systems capable of providing superior performance permitted are permitted. Many types of irregularities are prohibited. Nonstructural components that could cause injury must be provided with seismic restraint. Nonstructural systems required for facility function must be demonstrated to be capable of post-earthquake functionality. Special construction quality assurance measures are required.

Table 3 Occupancy

Category	Representative Buildings	Acceptable Risk
I	Buildings and structures that normally are not subject to human occupancy (e.g., equipment storage sheds, barns, and other agricultural buildings) and that do not contain equipment or systems necessary for disaster response or hazardous materials.	Low probability of earthquake-induced collapse.
II	Most buildings and structures of ordinary occupancy (e.g., residential, commercial, and industrial buildings) except those buildings contained in other categories.	Low probability of earthquake-induced collapse. Limited probability that shaking-imposed damage to nonstructural components will pose a significant risk to building occupants.
III	Buildings and structures that: • Have large numbers of occupants (e.g., high-rise office buildings, sports arenas, and large theaters), • Shelter persons with limited mobility (e.g., jails, schools, and some healthcare facilities); • Support lifelines and utilities important to a community's welfare; or • Contain materials that pose some risk to the public if released.	Reduced risk of earthquake-induced collapse relative to Occupancy Category II structures. Reduced risk of shaking-imposed damage to nonstructural components relative to Occupancy Category II structures. Low risk of release of hazardous materials or loss of function of critical lifelines and utilities.
IV	Buildings and structures that: • Are essential to post-earthquake response (e.g., hospitals, police stations, fire stations, and emergency communications centers) or • House very large quantities of hazardous materials.	Very low risk of earthquake induced-collapse. Low risk that the building or structure will be damaged sufficiently to impair use in post-earthquake response and recovery efforts. Very low risk of release of hazardous materials.

The intensity of earthquake shaking and other effects used to assign structures to a Seismic Design Category is determined using the national seismic maps previously presented in Figures 14 and 15. Figure 14 is used to determine a short-period shaking parameter, S_S. This acceleration parameter is the maximum shaking considered for the design of low-rise buildings located on sites conforming to a reference soil condition. Figure 15 is used to determine the 1-second period shaking parameter, S_1. This shaking parameter, also derived for sites conforming to a reference soil condition, is important to the design of taller buildings.

In order to determine a structure's Seismic Design Category, it is necessary to determine the value of the S_s and S_1 parameters at the building site, adjust those values to account for the soil conditions actually present at the building site, and then reduce the values by two-thirds to represent design-level ground shaking. The resulting design acceleration parameters are labeled S_{DS} and S_{D1}, respectively. In general, sites that have deep deposits of soft soils will have larger values of the design acceleration parameters than sites with shallow deposits of firm soils or near-surface rock. More discussion of these parameters appears below.

In communities where soil conditions vary, similar buildings constructed on different sites may be assigned to different Seismic Design Categories and this can result in very different seismic design requirements for similar buildings in the same city. Figure 29 provides a series of maps[3] of the United States and its territories showing the Seismic Design Category for low-rise Occupancy Category I and II structures located on sites with average alluvial soil conditions. This map is used in the *International Residential Code* (IRC). Structures of a higher Occupancy Category would be assigned to a higher SDC. Tall structures and structures on sites with other than average alluvial soils also may be assigned to different SDCs.

5.2 Site Class

Site soil conditions are important in determining Seismic Design Category. Hard, competent rock materials efficiently transmit shaking with high-frequency (short-period) energy content but tend to attenuate (filter out) shaking with low-frequency (long-period) energy content. Deep deposits of soft soil transmit high-frequency motion less efficiently but tend to amplify the low-frequency energy content. If the nature and depth of the various soil deposits at a site are known, geotechnical engineers can perform a site response analysis to determine the importance of these effects. For most sites, however, these effects can be approximated if the nature of soil at the site is known. The *NEHRP Recommended Seismic Provisions* uses the concept of Site Class to categorize common soil conditions into broad classes to which typical ground motion attenuation and amplification effects are assigned.

Site Class is determined based on the average properties of the soil within 100 feet (30 meters) of the ground surface. Geotechnical engineers use a variety of parameters to characterize the engineering properties of these soils, including general soil classifications as to the type of soil, (e.g. hard rock, soft clay), the number

[3]The Seismic Design Category maps that follow are those approved for inclusion in the 2012 edition of the *International Residential Code*. In the *International Building Code* and the *Provisions*, Categories D_0, D_1 and D_2 are combined into a single Category D.

of blows (N) needed to drive a standard penetration tool 1 foot into the soil using a standard hammer, the velocity (v_s) at which shear waves travel through the material as measured by on-site sonic and other tests, and the shear resistance of the soil (s_u) as measured using standard laboratory test procedures. Table 4 lists the six Site Classes recognized by the *NEHRP Recommended Seismic Provisions* and the engineering parameters used to define them. On many sites, the nature of soils will vary with depth below the surface.

Table 4 Site Class and Soil Types

Site Class	General Description	Shear Wave Velocity, v_s (ft/sec)	Blows/foot (N)	Shear strength, s_u (psf)
A	Hard rock	>5,000		
B	Rock	2,500-5,000		
C	Very dense soil and soft rock	1,200-2,500	>50	>2,000
D	Stiff soil	600-1,200	15-50	1,000 – 2,000
E	Soft clay soil	<600	<15	<1,000
F	Unstable soils			

Rock associated with Site Class A is typically found only in the eastern United States. The types of rock typically found in the western states include various volcanic deposits, sandstones, shales, and granites that commonly have the characteristics appropriate to either Site Class B or C. Sites with very dense sands and gravels or very stiff clay deposits also may qualify as Site Class C. Sites with relatively stiff soils including mixtures of dense clays, silts, and sands are categorized as Site Class D, and this is the most common site class throughout the United States. Sites along rivers or other waterways underlain by deep soft clay deposits are categorized as Site Class E. Sites where soils are subject to liquefaction or other ground instabilities are categorized as Site Class F and site-specific analyses are required.

As indicated above, the properties of the soils in the 100 feet below ground surface must be known to determine the Site Class, and this requires an investigation that includes drilling borings into the soil and removing samples of the soil at various depths in order to classify it. The *NEHRP Recommended Seismic Provisions* permits any site to be categorized as Site Class D unless there is reason to believe that it would be more properly classified as Site Class E or F. However, classification of a site as conforming to either Site Class A, B, or C generally will lead to a more economical structural design than an assumption that a site conforms to Class D because Site Classes A, B, and C produce less intense shaking than does Site Class D.

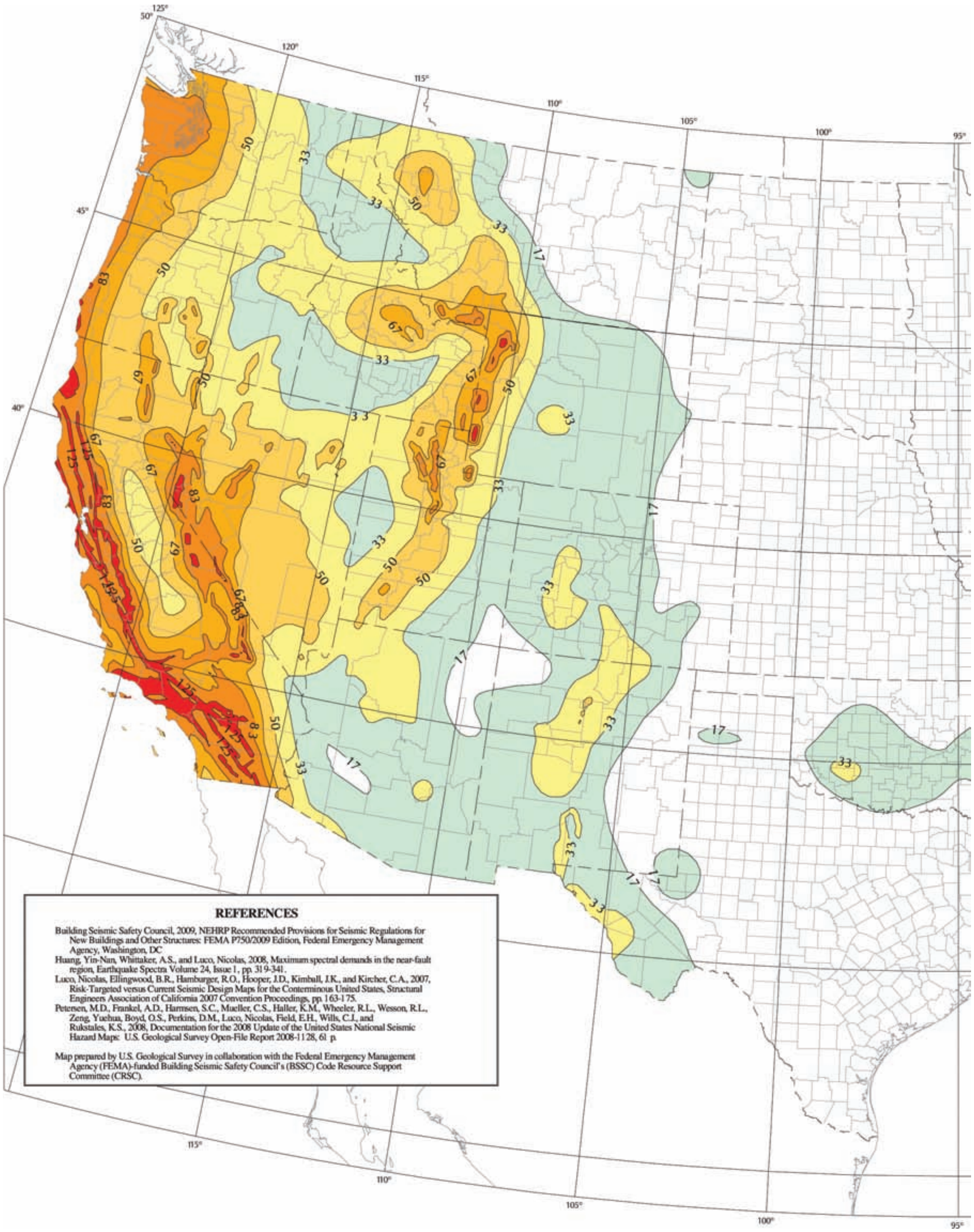
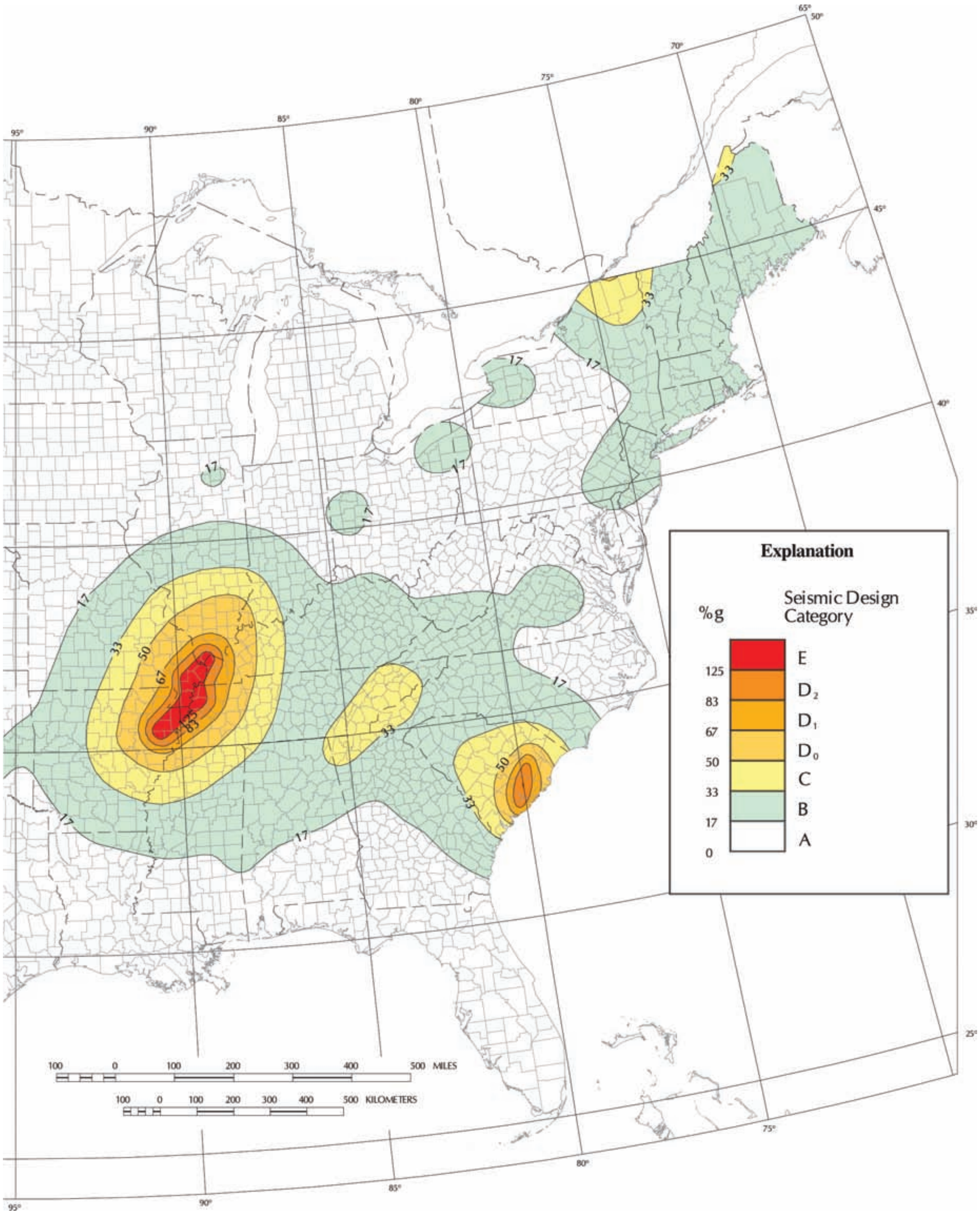


Figure 29 Seismic Design Categories for low-rise buildings of ordinary occupancy on alluvial soils.


Explanation
%g
Seismic Design Category
125
83
67
50
33
17
0
E
D_2
D_1
D_0
C
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A
100 0 100 200 300 400 500 MILES
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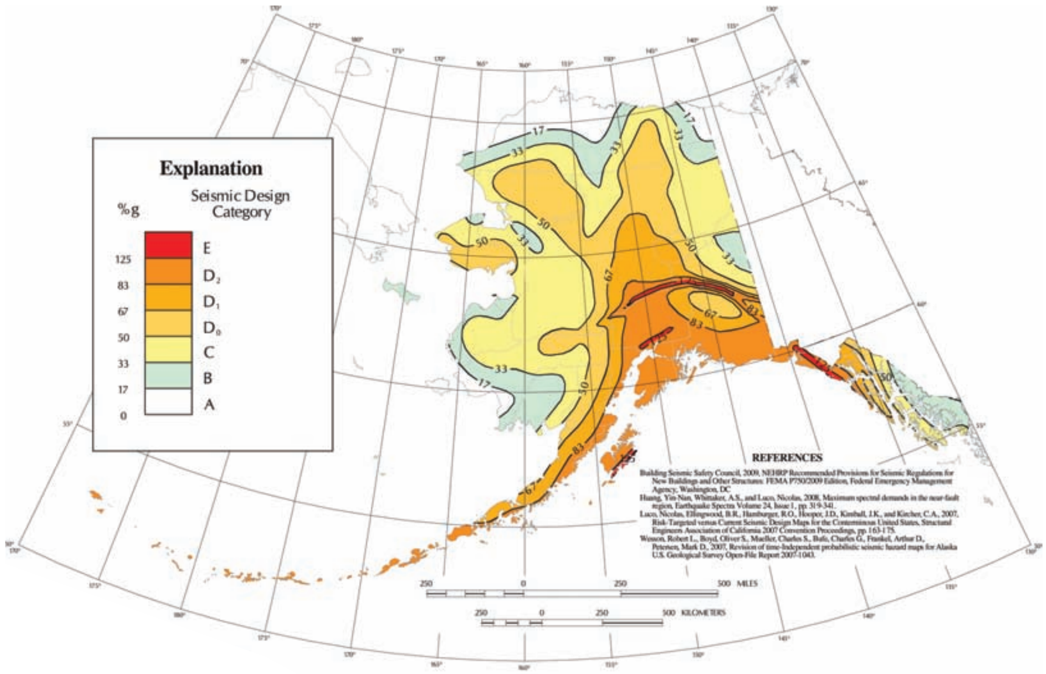


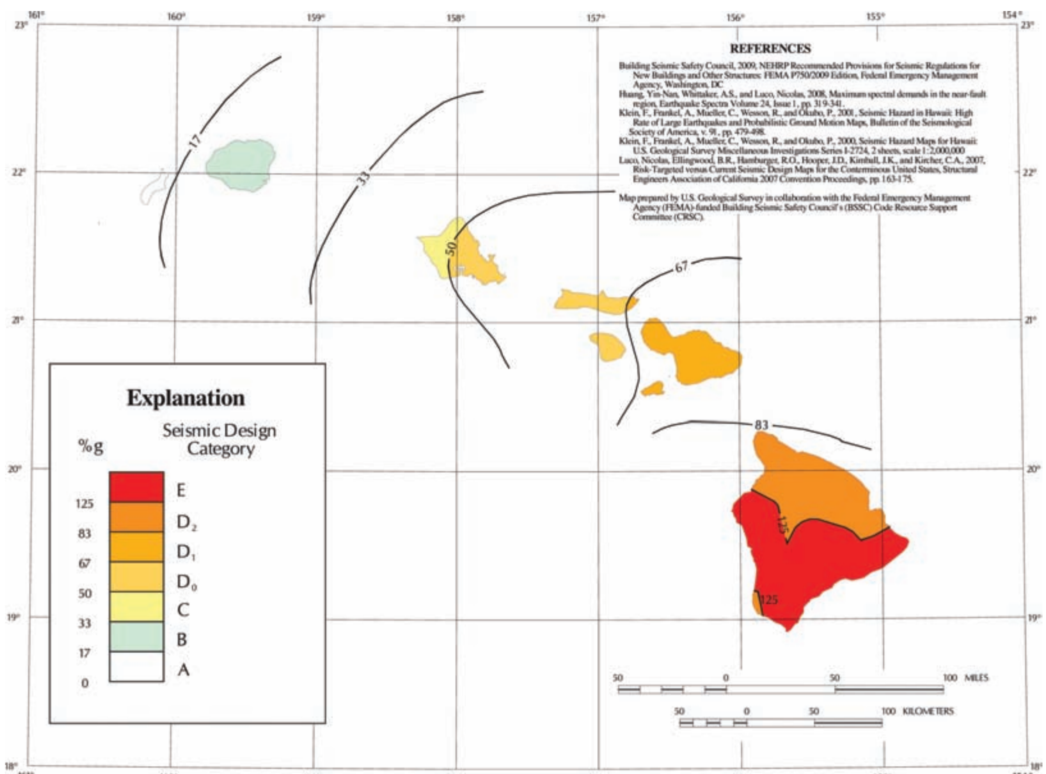
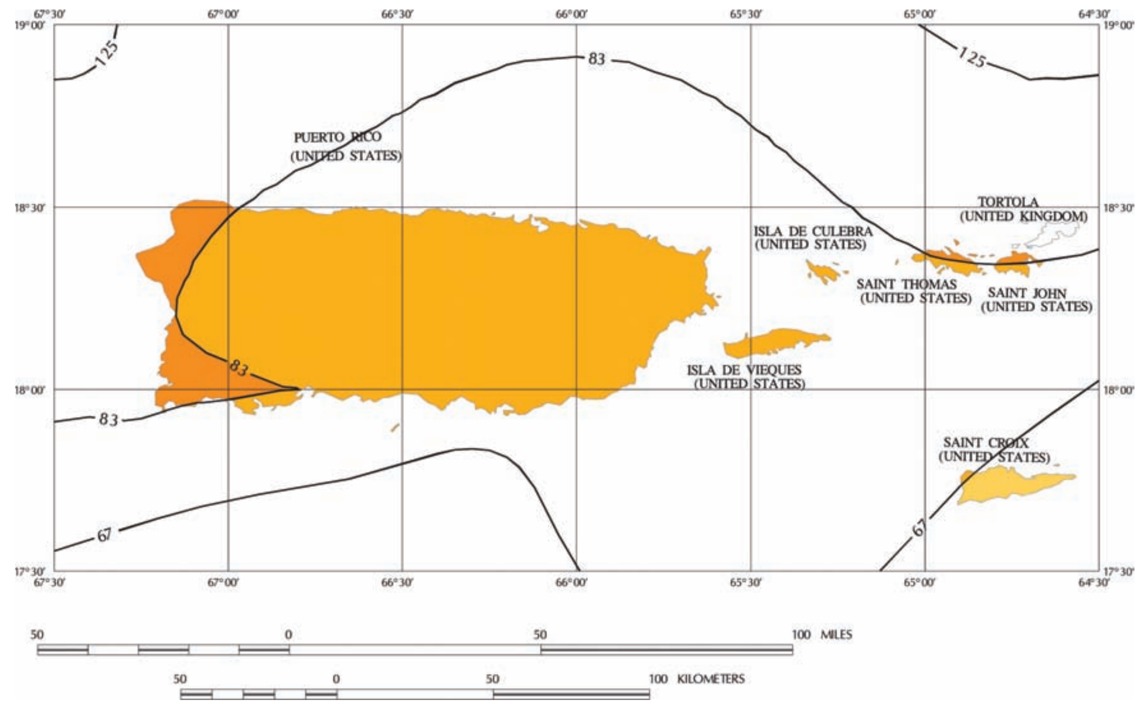


Figure 29 continued



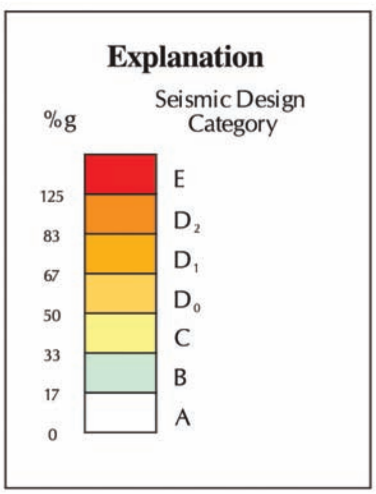


Figure 29 continued

5.3 Design Ground Motion

In order to determine the Seismic Design Category for a structure, it is first necessary to determine the design ground motion, which is one of the primary factors used to determine the required seismic resistance (strength) of structures and supported nonstructural components.

Design ground motion is defined by an acceleration response spectrum having a shape similar to that shown previously in Figure 10 and characterized by the following parameters:

- S_{DS} – short-period design response acceleration, in units of percent g
- S_{D1} – one-second period design response acceleration, in units of percent g
- T_s – transition period from constant response acceleration to constant response velocity, in units of seconds
- T_L - transition period from constant response velocity to constant response displacement, in units of seconds

Figure 30 is the generalized form of the design acceleration response spectrum showing each of these parameters. The values of S_{DS} and S_{D1}, respectively, are determined as follows:

$$S_{DS} = \tfrac{2}{3} F_a S_S \tag{1}$$

$$S_{D1} = \tfrac{2}{3} F_v S_1 \tag{2}$$

In these equations, F_a and F_v are coefficients related to the Site Class that indicate, respectively, the relative amplification or attenuation effects of site soils on short-period (high-frequency) and long-period (low-frequency) ground shaking energy. Tables 5 and 6 present the values of these coefficients for the Site Classes defined above.

S_s and S_1 are the mapped values of MCE_R spectral accelerations for reference soil conditions. The USGS maintains a web-based application accessible at http://earthquake.usgs.gov/research/hazmaps/ that will calculate values of S_s, S_1, S_{DS}, and S_{D1} based on input consisting of either geographic coordinates (latitude and longitude) or postal zip code and Site Class. It should be noted that the use of zip code to determine these acceleration parameters is not recommended in regions of the nation where structures are assigned to Seismic Design Category D or higher because there can be great variation in the value of these parameters across the area encompassed by a postal zip code. A number of internet sites include

look-up features for longitude and latitude of a site based on address; one such site is http://www.zipinfo.com/search/zipcode.htm.

Table 5 Values of Site Class Coefficient F_a as a Function of Site Class

	Value of Short-Period *MCE* Response Acceleration, S_S				
Site Class	$S_s < 0.25$	$S_s = 0.5$	$S_s = 0.75$	$S_s = 1.0$	$S_s \geq 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	0.9
F	Site specific study required.				

Table 6 Values of Site Class Coefficient F_v as a Function of Site Class

	Value of 1-Second *MCE* Response Acceleration, S_1				
Site Class	$S_1 \leq 0.1$	$S_1 = 0.2$	$S_1 = 0.3$	$S_1 = 0.4$	$S_1 \geq 0.5$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.7	1.6	1.5	1.4	1.3
D	2.4	2.0	1.8	1.6	1.5
E	3.5	3.2	2.8	2.4	2.4
F	Site specific study required.				

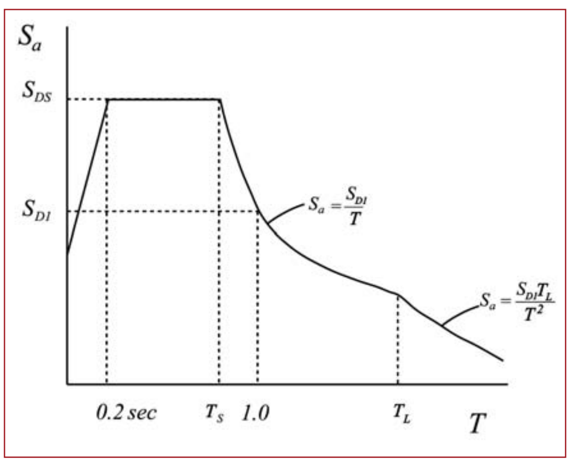


Figure 30 Generalized design response spectrum.

The value of T_L is obtained from a map prepared by the USGS based on the maximum magnitude earthquake anticipated to produce strong shaking in a region. Figure 31 presents this map of T_L values (in units of seconds) for the continental United States.

The value of T_S (in units of seconds) is calculated by the following equation:

$$T_S = {S_{D1}}/{S_{DS}} \tag{3}$$

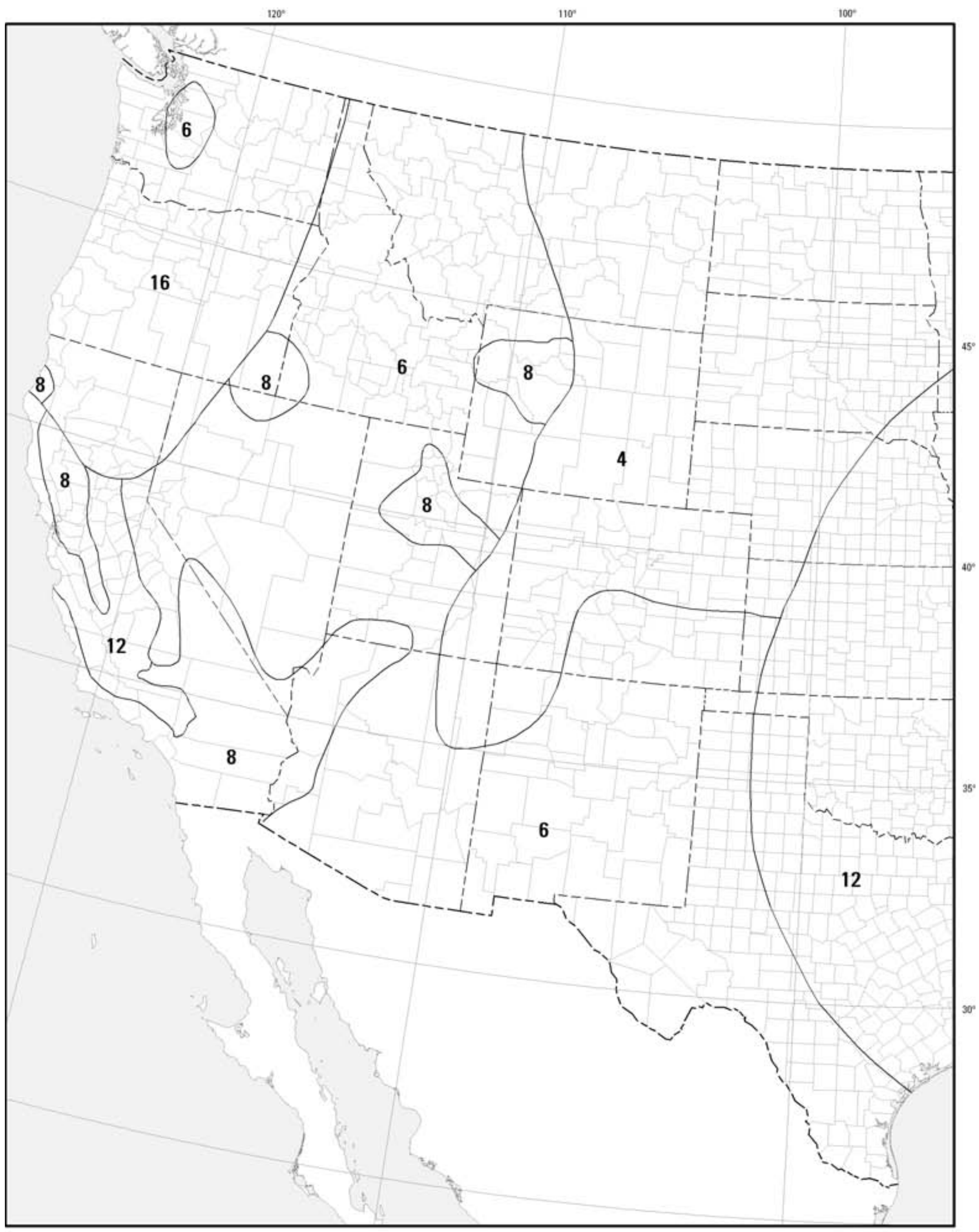


Figure 31 Map of long-period transition period, T_L, for the continental United States.


90°
80°
70°
50°
45°
40°
35°
30°
25°
100 0 100 200 300 400 500 Miles
100 0 100 200 300 400 500 Kilometers
4
12
6
8

5.4 Structural System Selection

The next step in the design process consists of selecting an appropriate seismic-force-resisting system (SFRS). As explained in Chapter 3, the seismic-force-resisting systems for building structures and nonbuilding structures with structural systems like buildings are categorized by construction material (e.g., concrete, masonry, steel, or wood), type of system (bearing wall, braced frame, moment frame, dual, or cantilever column), and level of seismic detailing (special, intermediate, ordinary, or not detailed for seismic resistance). Structures assigned to Seismic Design Category A can use any type of SFRS as long as the system is complete and provides minimum specified strength. Structures assigned to Seismic Design Categories B or higher must utilize one of the specific SFRSs or combinations of these systems listed in Table 12.2-1 of the ASCE/SEI 7 standard. This table lists more than 90 different structural systems providing designers with a wide range of choices.

Some types of SFRS have proven to exhibit undesirable behavior when subjected to very intense ground shaking; therefore, the use of these SFRSs in higher SDCs is restricted. Some structural systems are prohibited from use in these design categories and other structural systems are permitted only for buildings and structures meeting specific height and weight limitations. Some notable restrictions on structural systems include the following:

- Plain concrete and plain masonry bearing wall systems are not permitted in Seismic Design Categories C or higher.
- Ordinary concrete and ordinary masonry bearing wall systems are not permitted in Seismic Design Categories D or higher.
- Ordinary concentric braced steel frames are not permitted in Seismic Design Categories D and E for buildings in excess of 35 feet in height or in Seismic Design Category F for buildings of any height.
- Braced frames and walls of any material cannot be used as the only SFRS in structures exceeding 160 feet in height in Seismic Design Categories D, E, or F unless certain configuration limitations are met.
- Braced frames and walls of any material cannot be used as the only SFRS in structures exceeding 240 feet in height in Seismic Design Categories D, E, or F regardless of building configuration.

Many other limitations apply to the individual SFRSs listed in the ASCE/SEI 7 table.

In order to qualify as a particular SFRS, the structure's seismic-force-resisting elements must be designed and detailed to conform to the specific requirements contained in industry specifications. For example, special concentric braced steel frames must comply with the design requirements contained in Chapter 13 of AISC 341, *Seismic Provisions for Structural Steel Buildings*. Intermediate concrete moment resisting frames must be designed and detailed to conform to the requirements contained in Section 21.12 of ACI 318, *Building Code Requirements for Structural Concrete*. Table 12.2.1 of ASCE/SEI 7 references the mandatory specification requirements for each structural system. Part 1 of the *NEHRP Recommended Seismic Provisions* adds additional design and detailing requirements for some structural systems.

For nonbuilding structures with structural systems similar to buildings, ASCE/SEI 7 Table 15.4-1 provides an alternative set of limitations on system use that considers the reduced human occupancies and different characteristics of nonbuilding structures. ASCE/SEI 7 Table 15.4-2 provides similar information for nonbuilding structures that do not have structural systems similar to buildings.

All three of the ASCE/SEI 7 tables specify the values of the three design coefficients used to determine the required strength and stiffness of a structure's seismic-force-resisting system:

- R is a response modification factor that accounts for the ability of some seismic-force-resisting systems to respond to earthquake shaking in a ductile manner without loss of load-carrying capacity. R values generally range from 1 for systems that have no ability to provide ductile response to 8 for systems that are capable of highly ductile response. The R factor is used to reduce the required design strength for a structure.

- C_d is a deflection amplification coefficient that is used to adjust lateral displacements for the structure determined under the influence of design seismic forces to the actual anticipated lateral displacement in response to design earthquake shaking. The C_d factors assigned to the various structural systems are typically similar to, but a little less than, the R coefficients, which accounts in an approximate manner for the effective damping and energy dissipation that can be mobilized during inelastic response of highly ductile systems. Generally, the more ductile a system is, the greater will be the difference between the value of R and C_d.

- Ω_o is an overstrength coefficient used to account for the fact that the actual seismic forces on some elements of a structure can significantly exceed those indicated by analysis using the design seismic forces. For most structural systems, the Ω_o coefficient will have a value between 2 and 3.

5.5 Configuration and Regularity

The design procedures contained in the *NEHRP Recommended Seismic Provisions* were developed based on the dynamic response characteristics of structures that have regular configurations with a relatively uniform distribution of mass and stiffness and continuous seismic-force-resisting elements. To the extent that structures have nonuniform distribution of strength or stiffness and discontinuous structural systems, the assumptions that underlie the design procedures can become invalid. These conditions are known as irregularities, and structures that have one or more of these irregularities are termed "irregular structures."

Some irregularities trigger requirements for the use of more exact methods of analysis that better account for the effects of these irregularities on the distribution of forces and deformations in the structure during response to earthquake shaking. Other irregularities trigger requirements for portions of the structure to be provided with greater strength to counteract the effects of the irregularity. Still other irregularities have led to very poor performance in past earthquakes and are prohibited from use in structures assigned to Seismic Design Categories E or F.

The *Provisions* identifies two basic categories of irregularity: horizontal or plan irregularity and vertical irregularity. Horizontal irregularities include:

- Torsional irregularity – This condition exists when the distribution of vertical elements of the seismic-force-resisting system within a story, including braced frames, moment frames and walls, is such that when the building is pushed to the side by wind or earthquake forces, it will tend to twist as well as deflect horizontally. Torsional irregularity is determined by evaluating the difference in lateral displacement that is calculated at opposite ends of the structure when it is subjected to a lateral force.
- Extreme torsional irregularity – This is a special case of torsional irregularity in which the amount of twisting that occurs as the structure is displaced laterally becomes very large. Structures with extreme torsional irregularities are prohibited in Seismic Design Categories E and F.
- Re-entrant corner irregularity – This is a geometric condition that occurs when a building with an approximately rectangular plan shape has a missing corner or when a building is formed by multiple connecting wings. Figure 32 illustrates this irregularity.
- Diaphragm discontinuity irregularity – This occurs when a structure's floor or roof has a large open area as can occur in buildings with large atriums. Figure 33 illustrates this irregularity.

- Out-of-plane offset irregularity – This occurs when the vertical elements of the seismic-force-resisting system, such as braced frames or shear walls, are not aligned vertically from story to story. Figure 34 illustrates this irregularity.
- Nonparallel systems irregularity – This occurs when the structure's seismic-force-resisting does not include a series of frames or walls that are oriented at approximately 90-degree angles with each other.

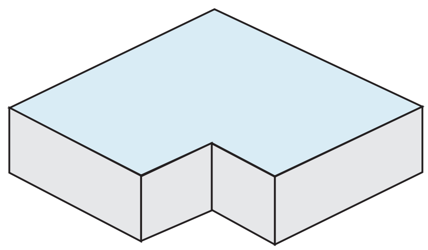


Figure 32 Re-entrant corner irregularity.

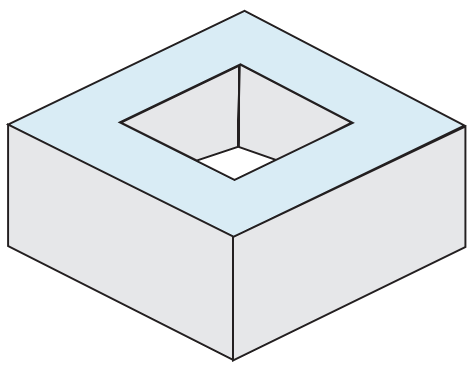


Figure 33 Diaphragm discontinuity irregularity.

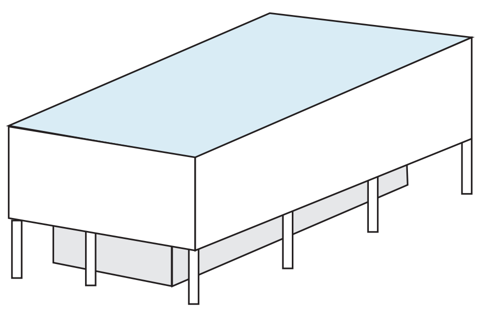


Figure 34 Out-of-plane offset irregularity.

Vertical irregularities include the following:

- Stiffness soft-story irregularity – This occurs when the stiffness of one story is substantially less than that of the stories above. This commonly occurs at the first story of multistory moment frame buildings when the architectural design calls for a tall lobby area. It also can occur in multistory bearing wall buildings when the first story walls are punched with a number of large openings relative to the stories above. Figure 35 illustrates these two conditions.

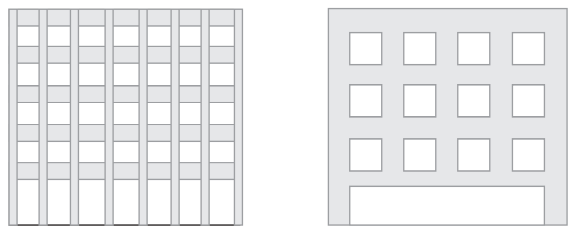


Figure 35 Examples of buildings with a soft first story, a common type of stiffness irregularity.

- Extreme stiffness soft-story irregularity – As its name implies, this is an extreme version of the first soft-story irregularity. This irregularity is prohibited in Seismic Design Categories E and F structures.

- Weight/mass irregularity – This exists when the weight of the structure at one level is substantially in excess of that at the levels immediately above or below it. This condition commonly occurs in industrial structures where heavy pieces of equipment are located at some levels. It also can occur in buildings that have levels with large mechanical rooms or storage areas.

- In-plane discontinuity irregularity – This occurs when the vertical elements of a structure's seismic-force-resisting system such as its walls or braced frames do not align vertically within a given line of framing or the frame or wall has a significant setback. Figure 36 provides examples of this irregularity.

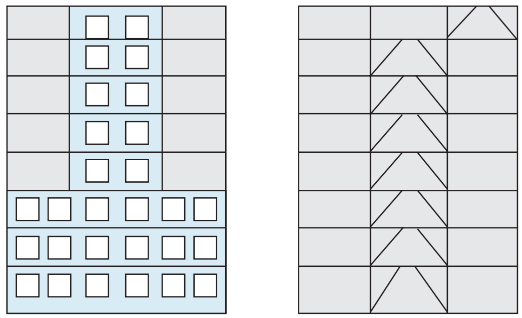


Figure 36 Examples of in-plane discontinuity irregularities.

- Weak-story irregularity – This occurs when the strength of the walls or frames that provide lateral resistance in one story is substantially less than that of the walls or frames in the adjacent stories. This irregularity often accompanies a soft-story irregularity but does not always do so.
- Extreme weak-story irregularity – As its name implies, this is a special case of the weak-story irregularity. Structures with this irregularity are prohibited in Seismic Design Categories E and F.

5.6 Required Strength

Earthquake shaking induces both vertical and horizontal forces in structures. These forces vary during an earthquake and, for brief periods ranging from a few tenths of a second to perhaps a few seconds, they can become very large. In structures assigned to Seismic Design Categories D, E or F, these forces easily can exceed the forces associated with supporting the structure's weight and contents. In keeping with the basic design philosophy of accepting damage but attempting to avoid collapse, the *NEHRP Recommended Seismic Provisions* requires that structures be provided with sufficient strength to resist specified earthquake forces in combination with other loads. Typically, engineers design a structure so that only some of the structure's elements (e.g., beams, columns, walls, braces) and their connections provide the required seismic resistance. As previously noted, the system created by these elements and their connections is called the seismic-force-resisting system (SFRS). The specific combinations of seismic load with other loads, including dead and live loads, that members of the SFRS must be proportioned to resist are specified in the ASCE/SEI 7 standard.

The specified earthquake forces are typically a fraction of the forces that design level earthquake shaking will actually produce in these structures. The magnitude of the specified earthquake forces and how they are calculated depends on the structure's Seismic Design Category, the type of structural system that is used, the structure's configuration, and the type of element or connection being designed. These are described briefly below.

5.6.1 Seismic Design Category A

Structures assigned to Seismic Design Category A are required to have adequate strength to resist three different types of specified forces:

- Global system lateral forces,
- Continuity forces, and
- Wall anchorage forces.

The global system lateral forces on elements of the SFRS are determined by applying a total static lateral force, equal to 1 percent (0.01) of the structure's weight and that of its supported nonstructural components and contents at each level, in each of two perpendicular directions. The forces in each direction are applied independently, but when the forces are applied in a given direction, they must be applied simultaneously at all levels. Figure 37 illustrates this concept.

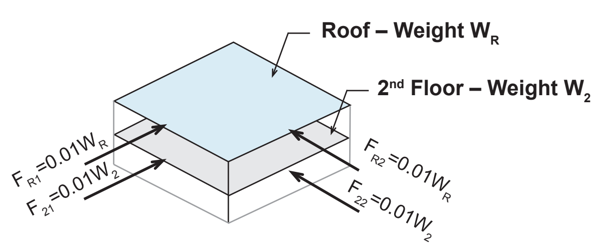


Figure 37 Required seismic design forces for Seismic Design Category A structures.

The design professional must use methods of elastic structural analysis to determine the individual forces in each of the SFRS elements and their connections under the influence of these global applied loads.

Continuity forces apply to those elements that "tie" or interconnect a small piece of a structure (e.g., a cantilevered deck to the main structure). The *NEHRP Recommended Seismic Provisions* specifies that such forces be equal to 5 percent (0.05) of the weight of the smaller portion of the structure as illustrated in Figure 38.

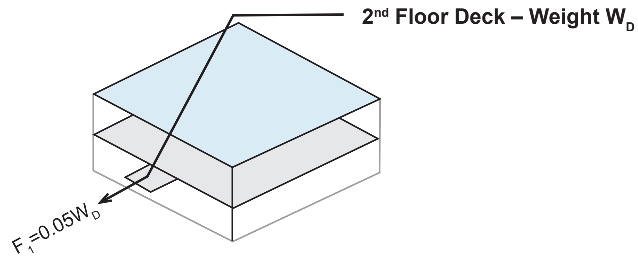


Figure 38 Continuity forces for Seismic Design Category A structures.

In addition to the forces illustrated in Figure 37, the *Provisions* also requires that each beam, girder, truss, or other framing member that provides vertical support for a floor or roof be connected to its supporting member with sufficient strength to resist a force applied along the axis of the member equal to 5 percent of the weight supported by the member.

Wall anchorage forces are intended to prevent the type of failure illustrated previously in Figure 16. The *Provisions* requires that all concrete and masonry walls in Seismic Design Category A structures be connected to the floors and roofs that provide out-of-plane support for the wall and that these connections have a strength not less than 280 pounds per linear foot of wall.

5.6.2 Seismic Design Category B

The forces illustrated above are sometimes called lateral forces because they result from actions that attempt to move the structure, or a portion of the structure, laterally to the side. Elements of structures in Seismic Design Category B must be designed for both lateral earthquake forces and vertical earthquake forces. Every structural element in these structures must be designed for stresses that result from vertical earthquake forces whether the element is part of the SFRS or not. These vertical forces are a result of vertical ground shaking. To account for these forces, the *NEHRP Recommended Seismic Provisions* requires that the stresses due to vertical earthquake shaking be taken as a fraction of the stresses in the members due to the weight of the structure itself and its permanent attachments (i.e., the dead load, *D*). The fraction is given by the formula:

$$E_V = 0.2 S_{DS} D \tag{4}$$

In this equation, E_v is the magnitude of forces due to vertical earthquake shaking, D is the magnitude of force due to the weight of the structure itself and its permanent attachments, and S_{DS} is the design spectral response acceleration at 0.2-second period determined in accordance with Equation 1.

The lateral earthquake forces are determined using procedures that approximate calculation of the structure's dynamic inelastic response to horizontal earthquake shaking. Several methods are available for calculating these lateral forces:

- Nonlinear response history analysis is a complex technique that calculates the forces and deformations induced in a structure in response to a particular earthquake record and accounts explicitly for the structure's dynamic and hysteretic properties. This is an elegant technique but it is computationally complex and, except for some structures incorporating seismic isolation or energy dissipation systems, it is not required so it is almost never used for the design of structures assigned to Seismic Design Category B.
- Linear dynamic analysis, commonly called response spectrum analysis (RSA), is substantially less complex than nonlinear response history analysis. It accounts for a structure's dynamic properties but only approximates the effects of nonlinear behavior. Its use is not required for the design of Seismic Design Category B structures but it is occasionally employed to design highly irregular or tall structures.
- The so-called equivalent lateral force (ELF) method is a simplification of the response spectrum analysis method, and it produces similar estimates of the earthquake forces and displacements for structures that are relatively regular and have primary response to earthquake shaking in their first mode. The first mode is the deformed shape associated with the lowest period at which a structure will freely vibrate. All structures in Seismic Design Category B can be designed using the ELF technique and it is the method most commonly used in this design category.

The actual magnitude of forces that act on a structure during earthquake shaking depends on the deflected shape of the structure as it responds to earthquake shaking and on the weight of the structure at each level. Figure 39 illustrates this concept for a three-story structure.[4]

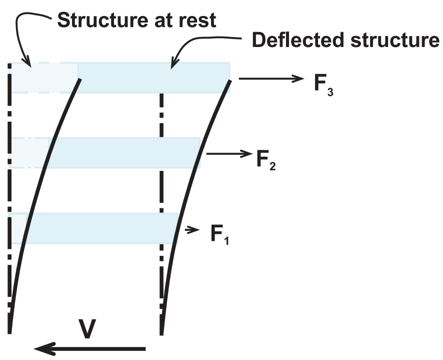


Figure 39 Distribution of lateral earthquake force in three-story structure.

In Figure 39, V is the total lateral earthquake force, which is sometimes called the "base shear." F_1 is the force applied at level 1, F_2 is the force applied at the second level, and F_3 is the applied force at the third level. According to the *Provisions,* the total lateral force or base shear, V, has a value given by the formula:

$$V = C_S W \tag{5}$$

In this equation, C_s is the seismic base shear coefficient and W is the structure's seismic weight. The seismic weight is equal to the weight of the structure and all permanently attached nonstructural components and systems including cladding, roofing, partitions, ceilings, mechanical and electrical equipment, etc. In storage and warehouse occupancies, W also includes 25 percent of the design storage load. For buildings with a flat roof in areas susceptible to a snow load of 30 psf or more, the seismic weight also includes 20 percent of the uniform design snow load.

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[4]The *Provisions* also contains a simplified version of the equivalent lateral force (ELF) procedure that can be used for some low-rise structures. This simplified design procedure is almost identical to the ELF procedure described above except that the equations used to determine the base shear forces (V) and story forces (Fi) are simplified, and it is not necessary to determine the deflections of the structural system. For buildings that do not have the irregularities described in Section 5.5, the simplified procedure and the full ELF procedure will produce very similar results; however, these results are sometimes relatively conservative. The simplified procedure cannot be used for buildings that have torsional irregularities because it does not provide for distribution of forces considering eccentric (torsional) effects. Therefore, before the simplified procedure can be used for a building with diaphragms that are not flexible, the building must be evaluated to determine if it is torsionally sensitive. In addition, since the simplified procedure does not include an evaluation of lateral deflection, it can be used only for buildings with relatively stiff structural framing systems including bearing wall systems and some types of building frame systems.

The base shear coefficient (C_s) depends on a number of factors including the structure's fundamental period of vibration (T), the structure's Occupancy Category (discussed in Section 5.1), and the type of seismic-force-resisting system used (discussed in Section 5.4). The fundamental period of vibration (T) is the amount of time, in seconds, the structure will take to undergo one complete cycle of motion if it is laterally displaced and released (similar to what is shown in Figure 39). For structures with fundamental periods of vibration less than the mapped value of T_L at their site, the base shear coefficient (C_s) is taken as the lesser of the value given by:

$$C_S = \frac{S_{DS}}{(R/I)} \tag{6}$$

$$C_S = \frac{S_{D1}}{(R/I)T} \tag{7}$$

where S_{DS} and S_{D1} are the spectral response acceleration parameters obtained from Equations 1 and 2 as indicated previously, R is the response modification coefficient discussed in Section 5.4; I is an occupancy importance factor, the value of which depends on the Occupancy Category previously described in Section 5.1, and T is the structure's fundamental period of vibration. The quantity R/I in Equations 6 and 7 is an expression of the permissible amount of inelastic structural response. The value of R is determined from the ASCE/SEI 7 standard based on the selected structural system. For buildings in Occupancy Category I or II, the importance factor (I) has a value of 1.0. For structures in Occupancy Categories III and IV, the importance factors are 1.25 and 1.5, respectively. Thus, for structures in higher occupancy categories, less inelastic behavior is permitted, which is consistent with the desired reduced risk of damage.

For structures with a fundamental period of vibration greater than T_L, the value of C_s can be determined using the formula:

$$C_S = \frac{S_{D1}T_L}{(R/I)T^2} \tag{8}$$

The value of the base shear coefficient for any structure, however, cannot be taken as less than the value obtained from the following formula:

$$C_S = 0.44 S_{DS} I \tag{9}$$

The lateral earthquake force (F_i) applied at each story *"i"* is obtained from the following formula:

$$F_i = \frac{w_i h_i^k}{\sum_{j=i}^{n} w_j h_j^k} V \qquad (10)$$

In Equation 10, the superscript k has a value of unity for structures with a fundamental period (T) less than or equal to 0.5 second, has a value of 2 for structures with a fundamental period greater than or equal to 2.5 seconds, and has a value that is linearly interpolated from these values for structures with a fundamental period that falls between these values. The value of the period can be determined using either a series of approximate formula that depend on the type of seismic-force-resisting system used or methods of structural dynamics that consider the distribution of the structure's mass and stiffness.

The fundamental period (T), seismic base shear force (V), and individual story forces (F_i) must be computed and applied independently in each of the structure's two primary orthogonal directions of response. The major vertical elements of the seismic-force-resisting system (frames or walls) will be aligned in these two orthogonal directions in most structures but, when this is not the case, any two orthogonal axes may be used. The story forces (F_i) are applied as static loads, and an elastic analysis is performed to determine the distribution of seismic forces in the various beams, columns, braces, and walls that form the vertical elements of the seismic-force-resisting system. These forces then are combined with the forces associated with dead, live, vertical seismic, and other forces using load combinations contained in the ASCE/SEI 7 standard and evaluated against permissible strengths contained in the various materials design standards referenced by ASCE/SEI 7. The design seismic forces on some elements in irregular structures must be amplified by the Ω_0 coefficient described previously. The purpose of design using these amplified forces is to avoid damage to elements whose failure could result in widespread damage and collapse of the structure.

The lateral forces (F_i) at each level are applied at a location that is displaced from the center of mass of the level by a distance equal to 5 percent of the width of the level perpendicular to the direction of application of the force. Figure 40 illustrates this concept. If the structure is not symmetrical, the 5 percent displacement of the point of application of the forces must be taken to both sides of the center of mass, and the design seismic forces on the elements must be taken as the highest forces obtained from either point of application. The purpose of this eccentric application of the forces is to account for any potential torsional loading that may

occur if, for example, one side of a building is occupied during earthquake shaking while the other side is vacant. This requirement also is intended to ensure that all structures have a minimum amount of resistance to torsional effects.

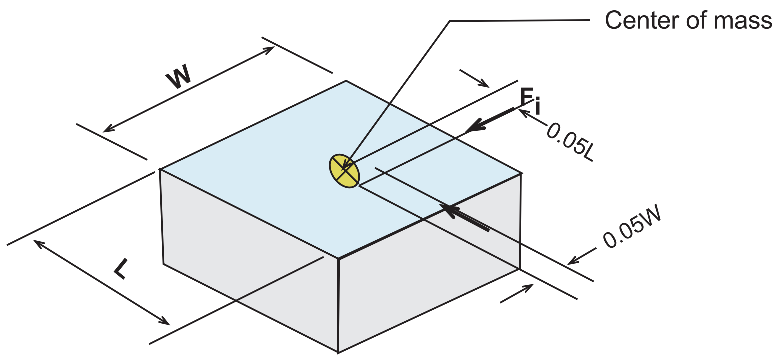

Figure 40 Eccentric application of story forces.

In addition to determining the seismic forces (E) on the vertical elements of the lateral-force-resisting system, the *NEHRP Recommended Seismic Provisions* requires determination of the seismic forces on the horizontal elements, typically called diaphragms. In most structures, the diaphragms consist of the floors and roofs acting as large horizontal beams that distribute the seismic forces to the various vertical elements. Diaphragms are categorized as being rigid, flexible, or of intermediate stiffness depending on the relative amounts of deflection that occur in the structure when it is subjected to lateral loading. Figure 41 shows the deflected shape of a simple single-story rectangular building under the influence of lateral forces in one direction. The roof diaphragm has deflection δ_L at the left side, δ_R at the right side and δ_C at its center. If the deflection at the center of the diaphragm (δ_C) exceeds twice the average of deflections δ_L and δ_R at the ends, the diaphragm can be considered flexible. The *Provisions* permits diaphragms of untopped wood sheathing or steel deck to be considered flexible regardless of the computed deflection. Diaphragms consisting of reinforced concrete slabs or concrete-filled metal deck that meet certain length-to-width limitations can be considered perfectly rigid. Other diaphragms must be considered to be of intermediate stiffness.

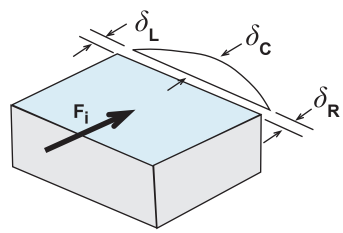

Figure 41 Deflection of diaphragm under lateral loading.

A flexible diaphragm is considered to distribute forces to the supporting vertical elements of the seismic-force-resisting system in the same way as a simple beam spanning between the vertical elements. For other diaphragms, the distribution of forces to the vertical elements must be considered on the basis of the relative rigidity of the vertical elements and the diaphragms using methods of structural analysis. Regardless, the diaphragm shears and moments at each level (i) of the structure must be determined for lateral forces using the following formula:

$$F_{px_i} = \frac{\sum_{j=i}^{n} F_j}{\sum_{j=i}^{n} w_j} w_{px_i} \tag{11}$$

In this formula, F_{px_i} is the total force to be applied to the diaphragm at level i, F_j is the seismic design force at each level j determined from Equation 10, w_{px_i} is the seismic weight of the structure tributary to the diaphragm at level i, and w_j is the seismic weight at each level j of the structure.

5.6.3 Seismic Design Category C

The design requirements for structures assigned to SDC C are almost identical to those for SDC B but there are a few important differences. First, some structural systems that can be used for SDC B are not permitted for SDC C because it is believed they will not perform adequately under the more intense ground motions associated with SDC C. In addition, SDC C structures with vertical seismic-force-resisting elements (shear walls, braced frames, moment frames, or combinations of these systems) located in plan such that they can experience significant seismic forces as a result of shaking in either of the major orthogonal building axes must be designed considering this behavior. An example of such a structure is one with columns common to intersecting braced frames or moment frames aligned in different directions. Another example is a structure with vertical elements aligned

in two or more directions that are not orthogonal to each other. The *NEHRP Recommended Seismic Provisions* requires this type of structure to be designed considering that forces can be incident in any direction. The *Provisions* permits satisfaction of this requirement by considering 100 percent of the specified design forces applied along one primary axis simultaneously with 30 percent of the specified design forces in an orthogonal direction. When this approach is used, at least two load cases must be considered consisting of 100 percent of the specified forces in direction A taken with 30 percent of the specified forces in direction B and 30 percent of the specified forces in direction A taken with 100 percent of the forces in direction B where directions A and B are, respectively, orthogonally oriented to each other.

For SDC C structures that are torsionally irregular, the 5 percent accidental torsion (discussed in the previous section) is amplified by an additional factor related to the amount of twisting that occurs when the design seismic forces are applied.

The *Provisions* also includes anchorage and bracing requirements for nonstructural components in SDC C structures and requires a site-specific geotechnical investigation to evaluate the potential for earthquake-induced ground instability including liquefaction, landsliding, differential settlement, and permanent ground deformation. If the geotechnical investigation report indicates that the site has significant potential to experience any of these instabilities, it also must include a discussion of potential mitigation strategies that can be used in the foundation design.

5.6.4 Seismic Design Categories D, E, and F

The requirements for determination of lateral seismic forces in SDCs D, E, and F are very similar to those for SDC C. The ELF method of analysis can be used for all structures of wood or cold-formed steel light frame construction and for all regular structures having a fundamental period (T) less than or equal to $3.5T_s$ as determined by Equation 3. The simplified analysis procedure also can be used for regular structures having three or fewer above-grade stories. Regardless of whether structures are regular or not, the design of SDC D, E, and F structures must include consideration of seismic forces acting concurrently in two orthogonal directions as discussed above.

For structures assigned to SDCs E and F, an additional lower bound is placed on the base shear coefficient (C_s) determined as follows:

$$C_{S_{min}} = 0.5\frac{S_1}{(R/I)} \tag{12}$$

This additional limit on base shear is intended to ensure that structures located close to major active faults have sufficient strength to resist the large impulsive forces that can occur on such sites.

The lateral seismic forces for structures that cannot be determined using either the complete ELF or the simplified procedures must be determined using either the response spectrum analysis (RSA) or the nonlinear response history procedures. A complete discussion of these procedures is beyond the scope of this document but can be found in the references at the conclusion of this report.

Finally, the strength design of structures assigned to SDC D, E, or F is subject to consideration of the structure's redundancy. A structure is considered to be sufficiently redundant if the notional removal of any single element in the structure's seismic-force-resisting system (e.g., a shear wall or brace) does not reduce the structure's lateral strength by more than one third and does not create an extreme torsional irregularity. If the configuration of a structure's seismic-force-resisting system meets certain prescriptive requirements, a rigorous check of the structure's redundancy is not required. If a structure does not meet these prescriptive requirements or the minimum strength and irregularity criteria described above, the required strength of all elements and their connections comprising the seismic-force-resisting system, other than diaphragms, must be increased by 30 percent.

5.7 Stiffness and Stability

If the simplified analysis procedure (see footnote in Section 5.6.2) is not used, Seismic Design Categories B through F structures must be evaluated to ensure that their anticipated lateral deflection in response to earthquake shaking does not exceed acceptable levels or result in instability. Two evaluations are required – the first is an evaluation of the adequacy of the structure's interstory drift at each level and the second is an evaluation of stability.

Interstory drift is a measure of how much one floor or roof level displaces under load relative to the floor level immediately below. It is typically expressed as a ratio of the difference in deflection between two adjacent floors divided by the

height of the story that separates the floors. Figure 42 illustrates the concept of interstory drift, showing this as the quantity δ_i, the drift that occurs under the application of the design seismic forces.

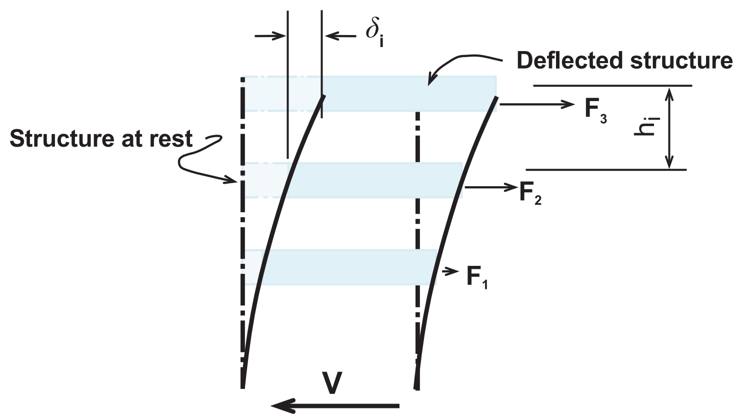

Figure 42 Interstory drift.

The *NEHRP Recommended Seismic Provisions* sets maximum permissible interstory drift limits based on a structure's Occupancy Category and construction type. The adequacy of a structure in this respect is determined by calculating the design story drift, Δ, as follows:

$$\Delta = \frac{C_d \delta_i}{I} \leq \Delta_a h_i \tag{13}$$

In this equation, δ_i is the computed interstory drift under the influence of the design seismic forces, C_d is the deflection amplification coefficient described in Section 5.4, and I is the occupancy importance factor. The acceptable drift ratio, Δ_a, varies from 0.007 to 0.025 depending on the structure's Occupancy Category and construction type.

Drift is also an important consideration for structures constructed in close proximity to one another. In response to strong ground shaking, structures located close together can hit one another, an effect known as pounding. Pounding can induce very high forces in a structure at the area of impact and has been known to cause the collapse of some structures. Therefore, the *NEHRP Recommended Seismic Provisions* requires that structures be set far enough away from one another and from property lines so that pounding will not occur if they experience the design drifts determined using Equation 13.

In addition, the *Provisions* requires an evaluation of a structure's stability under the anticipated lateral deflection by calculating the quantity Θ for each story:

$$\Theta = \frac{P_x \Delta}{V_x h_x C_d} \tag{14}$$

In this formula, P_x is the weight of the structure above the story being evaluated, Δ is the design story drift determined using Equation 13, V_x is the sum of the lateral seismic design forces above the story, h_x is the story height, and C_d is the deflection amplification coefficient described earlier. If the calculated value of Θ at each story is less than or equal to 0.1, the structure is considered to have adequate stiffness and strength to provide stability. If the value of Θ exceeds 0.1, the lateral force analysis must include explicit consideration of P-delta effects. These effects are an amplification of forces that occurs in structures when they undergo large lateral deflection. The limiting value for Θ ($\Theta_{\max}$) is calculated as:

$$\Theta_{\max} = \frac{0.5}{\beta C_d} \leq 0.25 \tag{15}$$

If the structure exceeds this limiting value, it is considered potentially unstable and must be redesigned unless nonlinear response history analysis is used to demonstrate that the structure is adequate. In the equation for Θ_{max}, β is calculated as the ratio of the story shear demand under the design seismic forces to the story shear strength. It can conservatively be assumed to have a value of 1.0. This requirement can become a controlling factor in areas of moderate seismicity for relatively flexible structures like steel moment-resisting frames.

5.8 Nonstructural Components and Systems

In Seismic Design Categories C and higher, nonstructural components and systems also must be designed for seismic resistance. The first step in the process is determining the component importance factor, I_p. Nonstructural components and systems that satisfy any of the following criteria are assigned an I_p of 1.5:

- The component is required for life-safety purposes following an earthquake. Fire sprinkler systems and emergency egress lighting and similar components are included in this category.

- The component contains hazardous material that, if released, could pose a threat to life safety. This would include piping carrying potentially toxic gases, tanks containing corrosive materials, laboratory equipment containing potentially harmful bacteria, and similar components.
- The component is attached to an Occupancy Category IV structure and is required for continued operation of the structure.

Some nonstructural components with a component importance factor of 1.5 can be further classified as "designated seismic systems." Designated seismic systems are those active mechanical and electrical components that must remain operable following an earthquake and those components containing hazardous components. In addition to meeting all of the other requirements for nonstructural components, the suppliers of designated seismic system components must provide certification that the components have either been subjected to shake-table testing or that earthquake experience data are available to demonstrate that the components will be capable of fulfilling their intended purpose following a design level earthquake.

Some nonstructural components including the following are exempt from seismic requirements:

- Mechanical and electrical components in Seismic Design Category C structures except those assigned an I_p of 1.5.
- Mechanical and electrical components in Seismic Design Category D, E, or F structures that are mounted at floor level, have an I_p of 1.0, weigh less than 400 pounds, and are connected to any piping or ductwork with flexible connections.
- Mechanical and electrical components in Seismic Design Category D, E, or F structures that have an I_p of 1.0, are mounted more than 4 feet above the floor, weigh less than 20 pounds, and are connected to any piping or ductwork with flexible connections.

Components that are not exempt must be installed in structures using anchorage and bracing that have adequate strength to resist specified seismic forces. In addition, components attached at multiple points in a structure that can move differentially with respect to one another must be able to withstand anticipated earthquake displacements without failing in a manner that would endanger life safety.

The required strength of component attachments is determined as follows:

$$F_p = 0.3 S_{DS} I_p W_p \leq \frac{0.4 a_p S_{DS} W_p}{(R_p/I_p)} \left(1 + 2\frac{z}{h} \right) \leq 1.6 S_{DS} I_p W_p \qquad (16)$$

In this formula, F_p is the required attachment force, I_p is the component importance factor, W_p is the weight of the component, S_{DS} is the design short-period response acceleration calculated in accordance with Equation 1, h is the height above grade that the component is mounted in the structure, z is the height above grade of the component's point of attachment, h is the total height of the structure; and a_p and R_p are component-specific coefficients obtained from the ASCE/SEI 7 standard that are intended to reflect the dynamic amplification of floor accelerations that some types of component can experience and the ability of some components to experience overstress without failure.

In addition to these general strength and deformation requirements, the *NEHRP Recommended Seismic Provisions* identifies design requirements for some architectural components including exterior glazing and ceiling systems. The requirements for exterior glazing are relatively new in the construction industry and are not familiar to many cladding system suppliers. They are intended to ensure that large quantities of exterior glazing do not break during earthquakes and fall onto occupied street and sidewalk areas.

5.9 Construction Quality Assurance

Post-earthquake investigations have shown that a considerable amount of the serious earthquake damage to modern structures has occurred, not because of design deficiencies, but rather because contractors did not construct structural elements and nonstructural components as required in the design drawings and specifications. In order to minimize this problem, the *NEHRP Recommended Seismic Provisions* requires formalized construction quality assurance measures as part of the design and construction process. Among the key points of these construction quality assurance measures are the following:

- The design professional of record is required to designate on the drawings those structural elements that are part of the seismic-force-resisting-system,
- The design professional of record is required to indicate designated seismic system nonstructural components on the drawings,
- The design professional of record or another qualified design professional must observe the construction of some critical elements to ensure that the design is properly interpreted and executed,
- The design professional of record is required to develop a formal Quality Assurance Plan that identifies the number and types of inspections and tests that must be performed during construction, and

- Qualified independent inspectors must perform special inspections of key elements to ensure that the construction is performed in accordance with the design intent.